Radiocarbon and stable isotope constraints on Last Glacial Maximum and Younger Dryas ventilation in the western North Atlantic

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[1] Foraminiferal abundance, ^{14}C ventilation ages, and stable isotope ratios in cores from high deposition rate locations in the western subtropical North Atlantic are used to infer changes in ocean and climate during the Younger Dryas (YD) and Last Glacial Maximum (LGM). The $\delta^{18}O$ of the surface dwelling planktonic foram *Globigerinoides ruber* records the present-day decrease in surface temperature (SST) of ~4°C from Gulf Stream waters to the northeastern Bermuda Rise. If during the LGM the modern $\delta^{18}O$/salinity relationship was maintained, this SST contrast was reduced to 2°C. With LGM to interglacial $\delta^{18}O$ changes of at least 2.2‰, SSTs in the western subtropical gyre may have been as much as 5°C colder. Above ~2.3 km, glacial $\delta^{13}C$ was higher than today, consistent with nutrient-depleted (younger) bottom waters, as identified previously. Below that, $\delta^{13}C$ decreased continually to −0.5‰, about equal to the lowest LGM $\delta^{13}C$ in the North Pacific Ocean. Seven pairs of benthic and planktonic foraminiferal ^{14}C dates from cores >2.5 km deep differ by 1100 ± 340 years, with a maximum apparent ventilation age of ~1500 years at 4250 m and at ~4700 m. Apparent ventilation ages are presently unavailable for the LGM < 2.5 km because of problems with reworking on the continental slope when sea level was low. Because LGM $\delta^{13}C$ is about the same in the deep North Atlantic and the deep North Pacific, and because the oldest apparent ventilation ages in the LGM North Atlantic are the same as the North Pacific today, it is possible that the same water mass, probably of southern origin, flowed deep within each basin during the LGM. Very early in the YD, dated here at 11.25 ± 0.25 (n = 10) conventional ^{14}C kyr BP (equal to 12.9 calendar kyr BP), apparent ventilation ages <2.3 km water depth were about the same as North Atlantic Deep Water today. Below ~2.3 km, four YD pairs average 1030 ± 400 years. The oldest apparent ventilation age for the YD is 1600 years at 4250 m. This strong contrast in ventilation, which indicates a front between water masses of very different origin, is similar to glacial profiles of nutrient-like proxies. This suggests that the LGM and YD modes of ocean circulation were the same. *INDEX TERMS:* 4267 Oceanography: General: Paleoceanography; 4576 Oceanography: Physical: Western boundary currents; 4532 Oceanography: Physical: General circulation; 4215 Oceanography: General: Climate and interannual variability (3309); 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; *KEYWORDS:* radiocarbon, ocean ventilation, western North Atlantic

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1. Introduction

[2] An important goal of paleoceanography is to document and understand the role of the ocean in climate change. It is known from studies of individual sediment cores, or clusters of a few cores in a region, that water masses of the western North Atlantic Ocean have varied on glacial-interglacial and millennial timescales, but much more attention has focused on the eastern basin of the North Atlantic [e.g., *Sarnthein et al.*, 1994] than the western North Atlantic. Most authors would agree that deep northern source waters were probably suppressed [*Duplessy et al.*, 1988; *Curry et al.*, 1988], flow of northern source intermediate waters was probably enhanced [*Oppo and Lehman*, 1993; *Came et al.*, 2003], and Gulf Stream properties were probably different during severe climate regimes of the late Quaternary [*Lynch-Stieglitz et al.*, 1999]. These changes are all climatically important because they affect heat and salt fluxes, and the heat released during water mass conversion. Despite more than two decades of effort into synoptic studies of the state of North Atlantic climate during glacial times, there are very few depth reconstructions of paleoproxy data for the western North Atlantic. The only available data come from the upper ocean reconstructions of *Slowey and Curry* [1995] in the Bahamas, and *Lynch-Steiglitz et al.* [1999] in the Florida Strait region. There is nothing in the western basin of the North Atlantic comparable to the synthesis of *Sarnthein et al.* [1994] for the eastern basin, yet it is the western basin where the most energetic elements of the ocean circulation occur.

[3] Here I report on time slice reconstructions for the Carolina slope, the Blake Ridge, and the Bahama Outer Ridge in the western subtropical North Atlantic (Figure 1).

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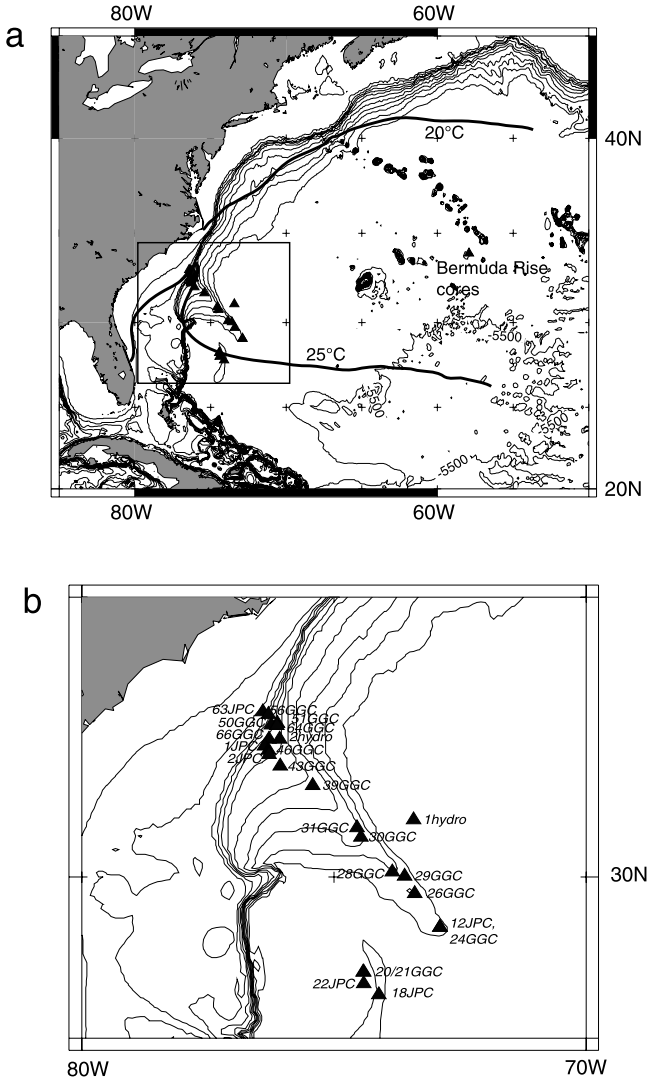

Figure 1. (a) Base map of core locations in the western North Atlantic. Isotherms from climatology of *Robinson et al.* [1979] are shown for 20 and 25°C. Note how SST at the shallow sites is dominated by water warmer than 25°C. (b) An expanded view of the Carolina Slope, Blake Ridge, and Bahama Outer Ridge.

These are sediment drift locations [*Flood*, 1978; *Markl and Bryan*, 1983; *Keigwin and Jones*, 1989], where western boundary currents [*Stommel*, 1958] are known to follow depth contours [*Heezen et al.*, 1966]. Above ~4000 m in this region the waters have mostly a northern source, whereas at greater depth there is a greater proportion of recirculated southern source water [e.g., *Hogg*, 1983]. By studying many cores from this region across a range of water depths as broad as a few km (Archive Table 1) it should be possible to determine the timing and extent of vertical migration in the benthic front between northern and southern source waters during the past 20 kyr.

[4] As discussed below, some of the best evidence for paleohydrographic change comes from the radiocarbon age differences between benthic (BF) and planktonic foraminifera (PF) from the Younger Dryas (YD) and the last glacial maximum (LGM). These age differences are known as ventilation ages, or top-to-bottom age differences. Here they will be called apparent ventilation ages, to emphasize the uncertainties both in accounting for the "preformed" ^{14}C content in the surface source region for deep waters, and in calculating projection ages [*Adkins and Boyle*, 1997]. After many years without new BF-PF radiocarbon pairs in the Atlantic Ocean, *Keigwin and Schlegel* [2002] showed that ventilation ages in the deep North Atlantic were nearly twice the figure reported previously by *Broecker et al.* [1990]. Those new results have been integrated into modeling and other studies that find the greatest consistency with various paleodata if the reduction in North Atlantic Deep Water (NADW) was indeed greater during the LGM than thought previously [*Broecker*, 2002; *Meissner et al.*, 2003]. However, the published data are still few and controversial. Many additional BF-PF data from new locations along the Carolina Slope, the Blake Ridge, and the Bahama Outer Ridge (latter two = BBOR) now show clearly that both LGM and YD ventilation ages were close to 1000 years below about 2300 m. No LGM pairs are available above that depth because of changing patterns of sedimentation on the continental slope as sea level fell, but YD pairs show ventilation ages of <500 years (similar to today) shallower than ~2.3 km. In general, these results support inferences made previously based on stable isotopes and trace metals in benthic foraminifera [*Boyle and Keigwin*, 1987; *Oppo and Lehman*, 1993].

2. Methods

[5] With some 40 sites sampled during R/V *Knorr* cruise 140 (KNR140) (Archive Table 1), we relied on several techniques to develop preliminary stratigraphies. Steve Lund (University of Southern California) measured the magnetic susceptibility on all cores. In addition to that, we pared down the list of cores using percent carbonate stratigraphy, observations of color and texture, and finally, stable isotope stratigraphy. The overall strategy was to identify and sample cores that had (1) the highest potential for temporal resolution, (2) sufficient foraminifera for stable isotope and radiocarbon analysis, and (3) the least evidence of down slope transport. Cores were typically sampled at 4- or 8-cm spacing so that the interval could be conveniently halved. In many cases, samples were eventually taken in 1-cm slices to focus on peaks in BF abundance. Samples were dried at 50°C, weighed, washed over a 63 μm screen, and forams were picked from the fraction >150 μm.

[6] Using standard methods [*Keigwin and Schlegel*, 2002], oxygen isotope analyses were done on the planktonic foram *Globigerinoides ruber* (150–250 μm), and occasionally on *Globigerinoides sacculifer. G. ruber* was more consistently present during cold episodes, but sometimes neither species was abundant enough and *Globorotalia inflata* was analyzed. The most abundant species of benthic foraminifera were picked and counted (*Uvigerina peregrina*, *Cibicidoides wuellerstorfi*, *Cibicidoides pachyderma*, and *Nuttalides umbonifera*). These species and the PF were usually analyzed for stable isotope composition as a check on their reliability prior to

Table 1. AMS ^{14}C Dates in This Study[a]

Core	Depth, cm	Interval, cm	Species	NOSAMS	Mass, mg	Notes	Conventional ^{14}C Age	Error 1 Sigma
01JPC	95.5	95–96	U. peregrina	35,602	6.5	YD	11,600	80
	95.5	95–96	G. ruber	35,601	8	YD	11,550	70
02PG	73	72–74	C. wuellerstorfi	33,893		YD	12,300	70
	72.5		G. ruber	35,699	small	YD	11,050	160
12JPC	79		mixed planktonics	38,857	8.1	YD	10,950	55
	79		N.u.+U.p.	37,671	2.3	YD	12,550	170
	231.5	230.5–232.5	N. umbonifera	33,891		LGM	17,300	95
	231	229.5–232.5	mixed planktonics	33,892		LGM	15,750	75
22JPC	169.5	168–171	G. inflata	25,804	6.2	LGM	15,700	95
	169.5	168–171	N. umbonifera	25,805	7.8	LGM	17,150	140
26GGC	37	34–40	G. ruber	35,603	7.1	not YD	7250	45
	37	34–40	U. peregrina	38,434		YD	12,000	55
	329	328–330	G. ruber	33,012	6.1	LGM	16,650	100
	329	328–330	N. umbonifera	33,011	5.1	LGM	17,650	140
30GGC	65		G. ruber	38,433		not YD	12,550	65
43GGC	178.5	177–180	G. ruber	32,900	5.9	LGM	18,350	95
	178.5	177–180	U. peregrina	32,899	4.8	LGM	18,950	120
50GGC	187	186.5–187.5	G. ruber	33,008	8.4	YD	11,200	50
	187	186.5–187.5	U. peregrina	33,007	5.5	YD	11,400	65
51GGC	280		G. ruber >250um	14,761	7.6		10,100	55
	290		G. ruber >250um	14,762	8.1		10,200	55
	300		G. ruber >250um	14,763	6.3		10,700	60
	310		G. ruber >250um	14,764	7.5	YD	11,350	65
	310	309–311	U. peregrina	19,141	4.8	YD	11,650	100
	312		U. peregrina	16,709	5	YD	11,500	75
	320		G. ruber >250um	14,765	9.5		11,950	60
	330		G. ruber >250um	14,766	6.5		12,250	100
	340		G. ruber >250um	14,767	8.4	contaminated sample	11,400	50
	350		G. ruber >250um	14,768	8.7		13,150	85
	360		G. ruber >250um	14,769	9.5		14,300	85
	370		G. ruber >250um	14,770	11.2		14,750	80
	380		G. ruber >250um	14,771	8.6	LGM	18,100	110
	380		G. sacculifera	35,604	6	LGM	17,600	100
	390		G. ruber >250um	14,772	4.8		17,500	100
	400		G. ruber >250um	14,773	6.9		20,200	130
	410		G. ruber >250um	14,774	7.7		23,600	190
	420		G. ruber >250um	14,775	7		25,500	230
56GGC	400	399–401	G. ruber	38,430	5.9	not YD	9810	55
	425	424.5–425.5	G. ruber	35,600	5.7	not YD	14,350	100
	510	509–511	G. ruber	35,605	6.8	~LGM	25,100	240
63JPC	80		N. pachyderma d.	35,597	5	not LGM	31,800	450
64GGC	180	179.5–180.5	G. ruber	33,006	8.7	YD	11,450	55
	180	179.5–180.5	U. peregrina	32,901	5.5	YD	10,950	60
	229		G. ruber	35,606	6.1	LGM	22,500	160
	242	241.5–242.5	G. ruber	33,889	6.8	not LGM	28,900	300
66GGC	89		U. peregrina	38,854	4.9	YD	11,750	60
	89		G. ruber	38,855	5.5	YD	11,600	50
67JPC	226		G. ruber	42,189		not LGM	45,800	1100

[a]Excluding *Keigwin and Schlegel* [2002] results.

dating by Accelerator Mass Spectrometry (AMS). Where possible, analyses were done on individual BF. Near the end of this study, we switched from our old VG Micromass 903 mass spectrometer to the VG Prism instrument at the National Ocean Sciences AMS Facility (NOSAMS). Methods are as described previously [*Keigwin*, 1998]. Where we have $\delta^{18}O$ data from both labs on LGM benthic foraminifera, it is apparent that the older instrument gave $\delta^{18}O$ that was greater by about 0.1‰ in LGM BF samples. This is despite the calibration of these instruments using both NBS-18 and NBS-19. We have not detected a systematic difference between the PF $\delta^{18}O$ results from these instruments, nor within Holocene BF. The $\delta^{13}C$ of ΣCO_2 in seawater was measured from three hydrocasts according to *McCorkle and Keigwin* [1994].

[7] Radiocarbon dating was done at the National Ocean Sciences Accelerator Mass Spectrometer (NOSAMS) facility at Woods Hole. A typical PF sample contained as many as a thousand individuals, whereas BF analyses used hundreds of specimens. Most samples were at least 5 mg of carbonate. Where surface-dwelling species were not sufficiently abundant, mixed species were analyzed, and in some deep water sites only *G. inflata* was available. As discussed by *Keigwin and Schlegel* [2002], ventilation ages using *G. inflata* are minima. Targets for dating were usually chosen based on the presence of abundance peaks in benthic foraminifera. If a suitably large peak was present (generally >5/g), and if the PF $\delta^{18}O$ looked appropriate for the YD or the LGM, then pairs of benthic and planktonic samples were submitted together. If there was some doubt about the age of

an event, the PF were dated first. If perfectly clean samples were not available, they were cleaned ultrasonically in distilled water. Following the earlier work of *Broecker et al.* [1988, 1990], and *Keigwin and Schlegel* [2002], ventilation ages are calculated as the age difference between BF and PF in conventional ^{14}C years. Radiocarbon ages were calibrated to cal years using CALIB v.4.3 [*Stuiver et al.*, 1998].

3. Stratigraphy and Chronology

3.1. Core Selection and Sedimentation

[8] Cores examined for this study fall into two groups. In the first group are those with PF $\delta^{18}O$ and BF abundances that proved useful for YD and LGM radiocarbon ventilation ages (Figures 2a–2j). The second group of cores (Figure 3) also has typical-looking isotope or carbonate stratigraphies. However, either BF abundance was too low, their abundance peaks were the wrong age for the present study (e.g., not YD), or they occurred very close to the core top and a large change in sedimentation rate was a cause for concern. All data will be archived with NOAA's NGDC database. Archive Table 2 lists core top stable isotope data, and Archive Table 3 lists LGM stable isotope data.

[9] Cores in the first group all showed consistent $\delta^{18}O$ changes and well-defined abundance peaks in *U. peregrina*, *C. wuellerstorfi*, and *N. umbonifera*. Those on the Carolina Slope (<2100 m) generally have Holocene sections at least a meter long, with very large BF abundance peaks during the LGM and deglaciation, whereas in deeper water the Holocene is generally thin, the pre-Holocene is expanded, and the BF are less common. Numerous dates at core 51GGC illustrate the slope changes in sedimentation rate over the past 20 kyr (Figure 4). Very low sedimentation rates during the LGM give way to increased rates during deglaciation and the Holocene. In the slope cores the LGM interval is condensed, oxidized (reddish), and coarsely granular, compared to more reducing and finer-grained overlying sediments. This is typical of other cores in the region [*Keigwin et al.*, 1998].

3.2. Faunal Data

[10] *U. peregrina* and *Cibicidoides* are prominent BF in cores above 3800 m, but below that *N. umbonifera* is more common. At slope depths, BF are rare in the Holocene, except near the core top where *U. peregrina* reaches a small maximum (e.g., Figures 2a and 3b). Both *Cibicidoides* and *U. peregrina* are much more common during deglaciation. These species show either broad intervals of high abundance (Figure 2c), or multiple peaks on the slope where the rate of deglacial sedimentation is relatively high, but by 2200–2400 m water depth these peaks collapse into sharp spikes (Figures 2e and 2f). This may be an artifact of accumulation rate because high deposition rate cores at 3 km reveal more structure during deglaciation [*Keigwin and Schlegel*, 2002]. Below 3800 m, sharp spikes in

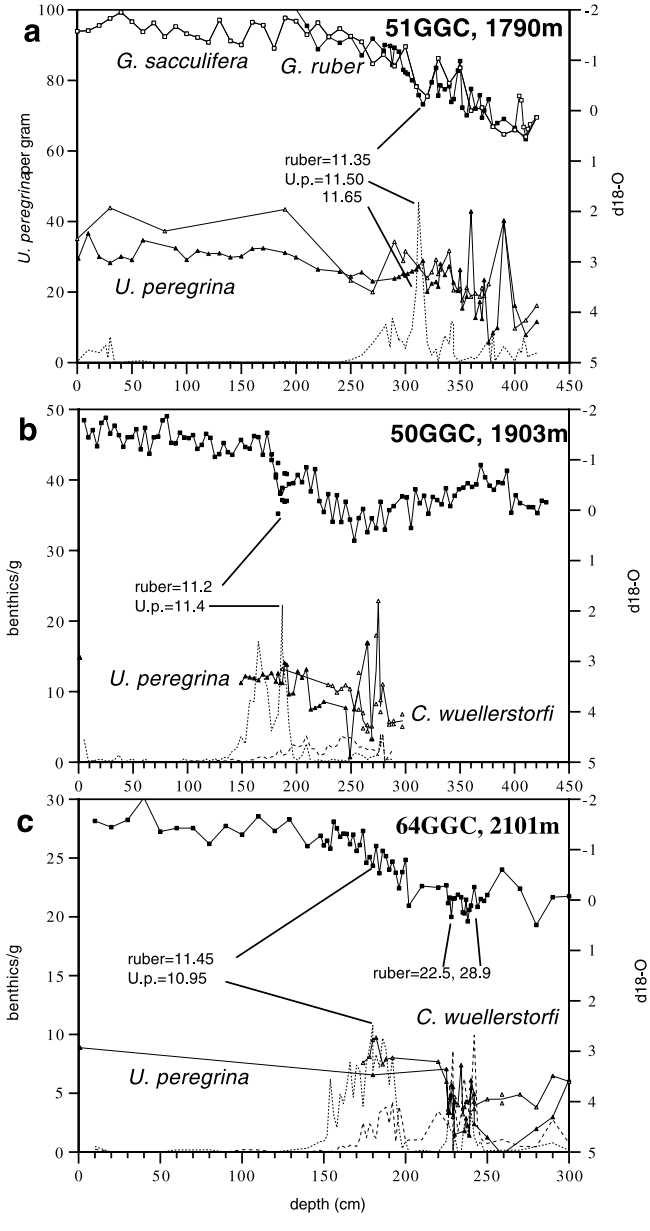

Figure 2. Oxygen isotope stratigraphies, abundance data on benthic foraminifera (BF), and ^{14}C pairs from 10 core sites used to determine apparent ventilation ages in this study. For each core, a $\delta^{18}O$ stratigraphy is based on the surface-dwelling planktonic foraminifera *G. ruber* (solid squares), and sometimes including *G. sacculifera* (open squares) or *G. inflata* (solid triangles, point down). Benthic foraminiferal abundance data are as follows: dotted line, *U. peregrina*; dashed line, *C. wuellerstorfi*; dash-dot line, *N. umbonifera*. Benthic $\delta^{18}O$ data are as follows: solid triangle, *U. peregrina*; open triangle, *C. wuellerstorfi*; open circle, *N. umbonifera*. The purpose of the benthic $\delta^{18}O$ data is to confirm the identification of the last glacial maximum, which was first based on the planktonic data. Where possible, BF $\delta^{18}O$ is based on individuals, so the scatter in the data is an indication of the extent of reworking. This was found to be a problem in the LGM interval at most sites <2300 m, where it prevented reliable ^{14}C dating. In this figure, ^{14}C data are shown only where dating was attempted to apply the apparent ventilation age method. Other ^{14}C data for Figure 2a are shown in Figure 4.

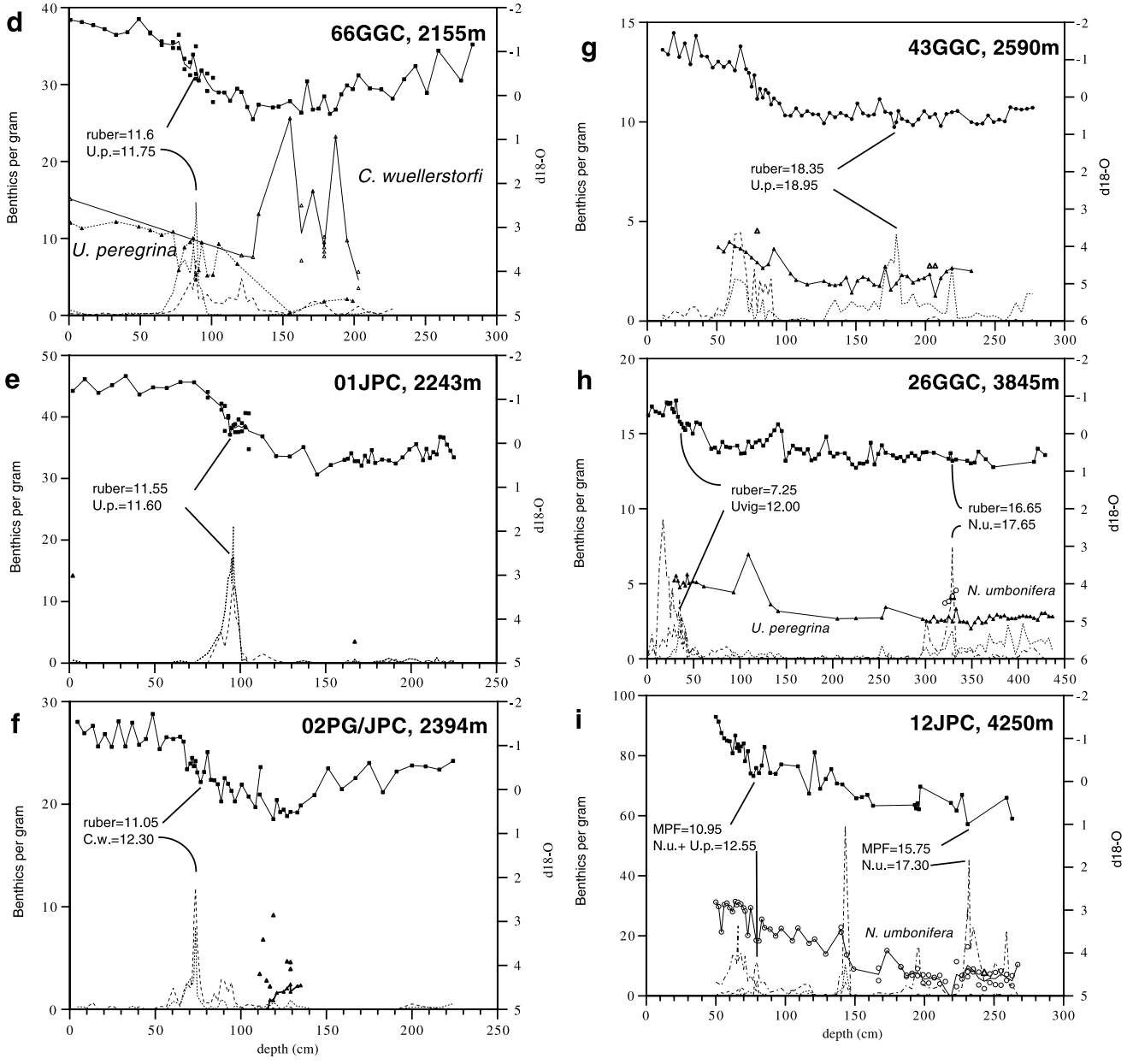

Figure 2. (continued)

N. umbonifera are the rule (despite high rates of sedimentation), and the other species are rare (Figures 2i and 2j).

[11] Downslope transport is a concern at some sites. Although shallow water BF such as *Trifarina* are common near the LGM at 51GGC, for example, they usually have poor preservation, infilling with glauconite, etc. The same holds true for displaced PF, and the presence of *Globorotalia menardii* and *Globorotalia tumida* in glacial age sediment signals this process. Because it was not certain that these species did not actually take refuge in Gulf Stream waters during the LGM, we used stable isotopes to test the idea that they grew during an earlier interglacial stage (Figure 5). Rare, well-preserved *G. menardii* and *G. tumida* were analyzed in two size classes from Holocene and LGM samples at 51GGC. Isotopically, the LGM specimens were indistinguishable from Holocene specimens, whether they were juvenile or adult. This indicates these *Globorotalia* must have been introduced to this site during the LGM from some interglacial outcrop up slope. It should be noted that, so long as the BF-PF ^{14}C method is based on peaks in BF abundance and the BF are in situ, downslope transport of older PF will tend to minimize ventilation ages.

3.3. Benthic Isotope Results

[12] Oxygen isotope results on BF are shown in Figures 2a–2j and 3. Radiocarbon analyses were not attempted on BF abundance peaks where the $\delta^{18}O$ data were noisy, and unfortunately this was the case at most slope sites during the LGM. For example, between 350 and

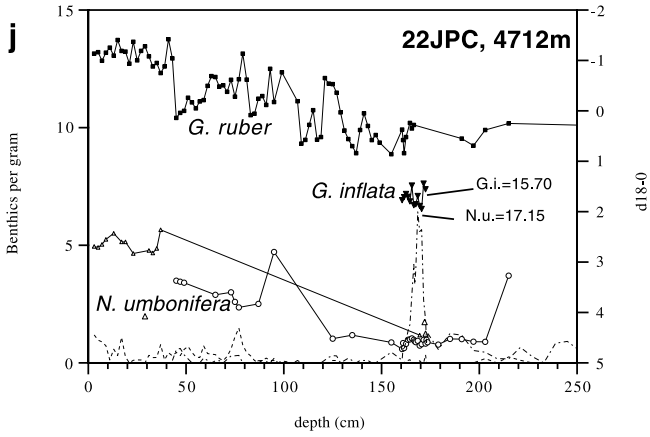

Figure 2. (continued)

400 cm there were unusual low $\delta^{18}O$ peaks in *U. peregrina* and *C. wuellerstorfi* at 51GGC (Figure 2a), and the same was found between 250 and 300 cm at 50GGC, 200–250 cm at 64GGC, and 150–200 cm at 66GGC (Figures 2a–2c and 2d, respectively). On the other hand, the benthic $\delta^{18}O$ data are quite consistent in the LGM at sites such as 43GGC (Figure 2g) and those that follow. This builds our confidence that the fauna is in situ and can be dated reliably on the continental rise.

3.4. Radiocarbon

[13] AMS ^{14}C data are listed in Table 1. Deeper than ~2.5 km, it was easy to identify LGM dating targets because the interval is ~5 kyr long, the $\delta^{18}O$ maximum is clear, and there is often a benthic abundance peak. However, our dated LGM events are not exactly synchronous. Note, for example, that the LGM level is as young as 15.65 ^{14}C cal years BP at core 22JPC (Figure 2j) and as old as 18.25 ^{14}C kyr BP at 43GGC (Figure 2g). Thus the LGM reconstruction discussed below represents more a time slab than a time slice.

[14] In contrast, the YD as identified here is a relatively discrete event. Many cores in Figures 2a–2j and 3 have BF abundance peaks late in the deglaciation, and some of those are associated with a maximum in PF $\delta^{18}O$ that would be consistent with YD cooling (Figures 2a, 2b, 2e, 2f, and 2i). AMS dates on the YD time slice range from 10,850 to 11,600 ^{14}C cal years BP (Table 2). However, in some deeper cores the Holocene interval is short and bioturbation may have been sufficient to mix young *G. ruber* downward without completely obliterating the YD benthic peak. Thus, for example, in 26GGC (Figure 2h) the peak in *G. ruber* at 37 cm is 7.25 ^{14}C kyr BP, even though the result on *U.peregrina* is typical for the water depth of that core (see below). In summary, by including an earlier date on the YD from the Bermuda Rise [*Keigwin et al.*, 1991], and more recent dates from other cores at the same location [*Came et al.*, 2003; *McManus et al.*, 2004] with new data from the continental margin, we find that the average of 10 PF dates from the YD BF peak around the western subtropical North Atlantic is 11.25 ± 0.25 (1σ) conventional ^{14}C kyr BP (Table 2). Assuming no additional reservoir effect ($\Delta R = 0$), this calibrates to ~12.9 cal years BP, the very beginning of the YD.

4. Discussion

4.1. Stable Isotope Paleoceanography

4.1.1. Surface Reconstructions

[15] PF $\delta^{18}O$ (mostly *G. ruber*) from core tops in the study area gradually increases by about 0.5‰ with water depth (Figure 6). Because this pattern is similar to both the 0.5°C decrease sea surface temperature (SST) offshore, and the 0.5 psu increase in salinity [*Robinson et al.*, 1979], it cannot be uniquely ascribed to one or the other. However, the core top pattern of PF $\delta^{18}O$ is similar to that expected for equilibrium precipitation of calcite. Using the *Robinson et al.* [1979] climatology, we calculated the $\delta^{18}O$ of calcite precipitated in equilibrium with annual average surface water, according to the methods used previously for Sargasso Sea waters over the Bermuda Rise [*Keigwin*, 1996]. *Deuser* [1987] found that *G. ruber* calcite near Bermuda is lower than predicted $\delta^{18}O$ by ~0.2‰, and that the $\delta^{18}O$ of this species reflected annual average SST. Indeed, the $\delta^{18}O$ for the BBOR locations deeper than 3 km is close to this offset (perhaps 0.3‰). However, core sites shoreward of the 3 km isobath are closer to 0.5‰ from the equilibrium line (Figure 6). This suggests that either the "vital effect" for *G. ruber* changes from Gulf Stream waters over the Carolina Slope to the open Sargasso Sea, or there is a summertime bias in the production of *G. ruber*, or the deeper core tops are less representative of modern conditions that the shallower ones. Finally, it should be noted that the nearshore Holocene data from Blake Ridge are about 1.0‰ lower than the Holocene on the Bermuda Rise [*Keigwin*, 1996], consistent with the ~4°C SST contrast between these locations today. Thus, despite some small and possibly variable disequilibrium, $\delta^{18}O$ of *G. ruber* is likely to be an excellent proxy for SST.

[16] In general, the LGM *G. ruber* $\delta^{18}O$ increases seaward in a manner similar to the Holocene data, but one notable feature in Figure 6 is the large difference between the LGM and Holocene. Fourteen pairs give an average $\delta^{18}O$ difference of 2.0‰ between the LGM maximum and the core top. This is a conservative estimate because the core top is not always the lowest $\delta^{18}O$, and the cores were not sampled and analyzed specifically for this purpose. Cores with the most complete Holocene sections, such as 50 and 51 GGC, have $\Delta\delta^{18}O$ of 2.23 and 2.21‰, respectively (Figures 2a and 2b). If the LGM ice volume effect was only 1‰, as recent pore water studies indicate [*Adkins et al.*, 2002], then there is scope for SST depression of 5°C during the LGM if there were no local salinity ($\delta^{18}O$ water) changes. Because Gulf Stream waters are tropical in origin, these results would suggest the tropical North Atlantic must have been substantially colder during the LGM, as has been argued in the past decade for many other low latitude locations [e.g., *Mix et al.*, 1999]. The fact that the LGM data are the same, from far offshore on Blake Ridge (>3 km water depth) to the Bermuda Rise, would indicate that at that time the western Sargasso Sea was more uniformly cool than it is today.

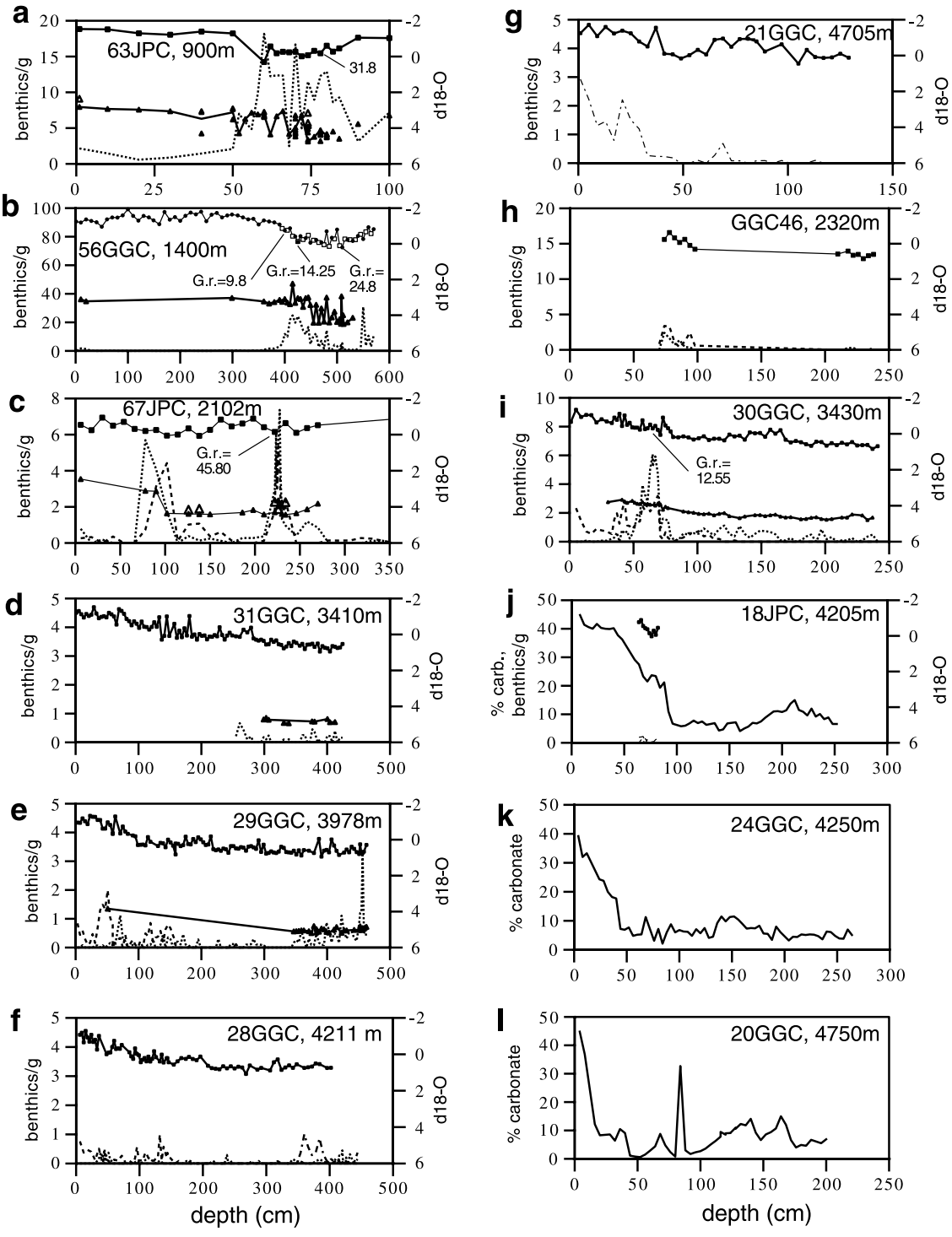

Figure 3. Data from 11 additional cores in the study region, using symbols as in Figures 2a–2j. For the three deepest cores, percent carbonate stratigraphy is shown as a solid line. It was thought cores in this figure would contribute to the ^{14}C ventilation synthesis, but either the benthic abundance peaks were too small to date, or the planktonic ages showed them to be neither YD nor LGM.

4.1.2. Deep Hydrography

[17] As expected, stable isotope ratios in core top BF show some systematic trends (Figure 7). *U. peregrina*, which is large, abundant, and consistently present at Carolina Slope depths, approximately reflects the trend of equilibrium precipitation of calcite, with some offset (Figure 7a). In contrast, *C. wuellerstorfi*, the preferred species for $\delta^{13}C$ analysis, is discontinuously present and

Table 2. Ventilation Age Data for YD and LGM Intervals

Water Depth, m	Core	YD PF	YD BF	YD BF-PF	±1s	LGM PF	LGM BF	LGM BF-PF	±1s
1790	51GGC	11,350	11,650	300	120				
1903	50GGC	11,200	11,400	200	80				
2101	64GGC	11,450	10,950	−500	70				
2155	66GGC	11,600	11,750	150	78				
2243	01JPC	11,550	11,600	50	110				
2394	02PG	11,050	12,300	1250	180				
2590	43GGC					18,350	18,950	600	150
2972	37JPC					15,750	16,550	800	95
2972	37JPC					18,250	19,300	1040	120
2975	39GGC	11,350	12,270	920	80	16,900	18,150	1250	120
3845	26GGC		12,000			16,650	17,650	1000	170
4250	12JPC	10,950	12,550	1600	180	15,750	17,300	1550	120
4600	KNR 31 GPC5	11,150	11,800	650	360				
4600	OCE326 GGC5	10,850		950	200				
4712	22JPC					15,700	17,150	1450	170

the $\delta^{18}O$ of it and *C. pachyderma* reveal a scatter of ∼0.5‰ that is not evident in *U. peregrina* where the depth range of the two species overlaps. Without stained (live) specimens recovered by box cores or multicores, it is not possible to determine whether this is due to variable disequilibrium effects, bioturbation, or reworking.

[18] *Cibicidoides* $\delta^{13}C$ is close to the $\delta^{13}C$ of ΣCO_2 of seawater in core tops from above 3 km, but it is extremely variable below 3 km (Figure 7b). Variable offsets from the $\delta^{13}C$ of seawater have been noted previously from the Bermuda Rise [*Keigwin et al.*, 1991; *Keigwin and Boyle*, 2000], but these new data suggest the problem may be widespread deep on the Blake Ridge as well. Beginning with *Zahn et al.* [1986], many studies have shown that the $\delta^{13}C$ of *U. peregrina* is affected by carbon rain rate and perhaps also by low $\delta^{13}C$ in pore water [*Corliss*, 1985]. Usually this is shown in time series, but the core top data from the Carolina Slope (Figure 7b) clearly show minimum $\delta^{13}C$ centered at about 1 km. Most likely, this pattern reflects the organic carbon content of surface sediments, which reaches a maximum along the continental margin from New England to the south Atlantic Bight in the 1–2 km depth range [*Gorsline*, 1963; *Walsh et al.*, 1988]. These data are consistent with the suggestion of *Miller and Lohmann* [1982] that *Uvigerina* is most closely associated with organic carbon content of sediments.

[19] Despite the uncertainties of core top calibration in the BBOR data set, the LGM time slice reconstruction appears reliable (no YD reconstructions are presented here because only a few sites have a clear abundance maximum in *C. wuellerstorfi*). BF $\delta^{18}O$ decreases by ∼1.0‰ from 4.7 km to 1 km (Figure 7c), and *Cibicidoides* $\delta^{13}C$ decreases by ∼2‰ (Figure 7d). There is some evidence for an abrupt decrease in $\delta^{13}C$ of *C. wuellerstorfi* between 2.0 to 2.3 km (Figure 7d), as noted previously by others who inferred that during glacial times the North Atlantic must have been better ventilated at intermediate depths by Glacial North Atlantic Intermediate Water (GNAIW) [*Boyle and Keigwin*, 1987; *Oppo and Fairbanks*, 1987; *Oppo and Lehman*, 1993; *Slowey and Curry*, 1995]. *Oppo and Lehman* [1993] showed the transition was very abrupt in the subpolar North Atlantic, centered on ∼2 km, and this contrasts with the subtropical results here that decrease continually with depth. Although the *Oppo and Lehman* [1993] reconstruction did not extend deeper than ∼2.5 km (nor did that of *Slowey and Curry* [1995]), the LGM minimum at Deep Sea Drilling Project Site 607 is ∼0.5‰ [*Raymo et al.*, 2004], the same as the nearby *Oppo and Lehman* [1993] results from 1 km shallower. Thus the $\delta^{13}C$ differences between the western subtropical North Atlantic and the northern North Atlantic during the LGM are probably real and reflect the much older deep waters in the deep western basin. Patterns of $\delta^{13}C$ all along the western Atlantic are discussed more fully by W. B. Curry and D. Oppo (Glacial water mass geometry and the distribution of $\delta^{13}C$ of ΣCO_2 in the western Atlantic Ocean, submitted to *Paleoceanog-*

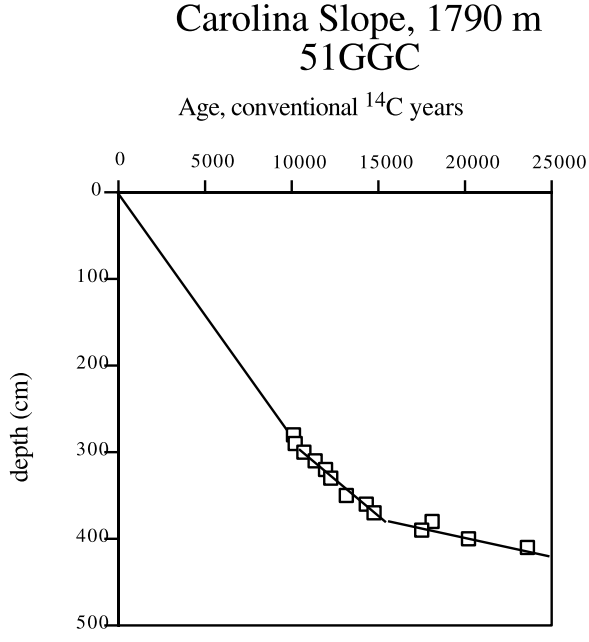

Figure 4. Age-depth relationship for core 51GGC on the Carolina Slope. As with other cores from slope depths, the Holocene rate of accumulation is high (in this case about 30 cm/kyr), the deglacial rate is moderate (∼20 cm/kyr), and the LGM interval is condensed (∼4 cm/kyr). The low LGM sedimentation rate, combined with the evidence for reworking (Figure 5), has precluded a reliable apparent ventilation age for the LGM at slope depths.

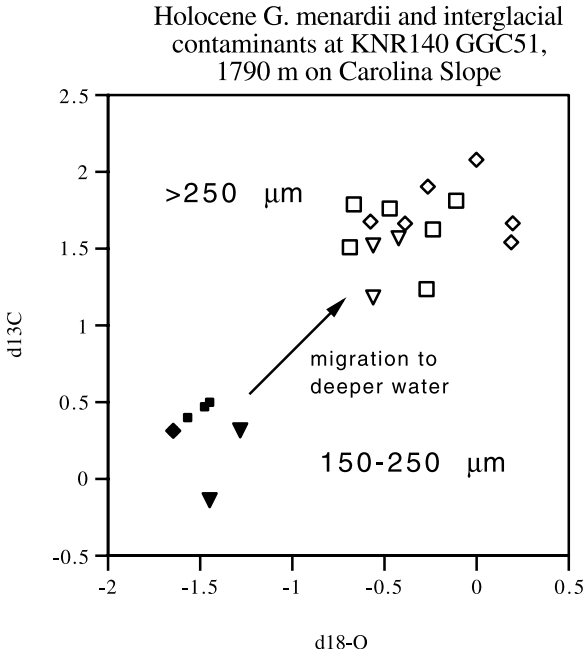

Figure 5. Scatterplot of $\delta^{18}O$ and $\delta^{13}C$ results on *G. menardii* and *G. tumida* from the Holocene and LGM sections of core 51GGC. Specimens were arbitrarily lumped into two size categories, because of possible size sorting in down slope transport. Solid symbols are small (juvenile) Holocene *G. tumida* (large diamond, four individuals), small Holocene *G. menardii* (squares, 8–10 individuals), and small LGM *G. menardii* (triangles, 10 individuals). Open symbols are large single LGM *G. menardii* (triangles), large single Holocene *G. menardii* (squares), and large single Holocene *G. tumida*. Regardless of size fraction, the samples from the Holocene and LGM intervals are indistinguishable. This shows that specimens found in the LGM interval must have been transported from interglacial outcrops shallower on the slope, which is also consistent with those specimens that had poorer preservation, glauconite, etc. [*Gorsline*, 1963]. The shift in isotope results between the two size fractions probably results from larger specimens living in deeper water. Because all specimens in this figure had excellent preservation, this test was done to reject the hypothesis that these *Globorotalia* spp. actually lived in Gulf Stream waters during the LGM. It also shows that poor preservation alone is not sufficient to identify and reject all reworked specimens.

raphy, 2004, hereinafter referred to as Curry and Oppo, submitted manuscript, 2004).

[20] The $\delta^{13}C$ of *U. peregrina* shows nothing like the familiar pattern in *C. wuellerstorfi*; this argues against the usefulness in trying to apply isotopic corrections among these species. Directly comparing the Holocene and LGM data shows that the $\delta^{13}C$ at intermediate depths was a few tenths‰ greater during the LGM, but this is a minimum difference because of the deglacial secular change in the $\delta^{13}C$ of ΣCO_2 of about 0.3‰ [*Duplessy et al.*, 1988]. Thus the $\delta^{13}C$ data indicate substantially better ventilation at intermediate depths by GNAIW than by upper NADW today [*Came et al.*, 2003; *Marchitto et al.*, 1998; Curry and Oppo, submitted manuscript, 2004].

4.2. Radiocarbon and Apparent Ventilation Ages

[21] Radiocarbon is a more direct tracer for ocean ventilation than nutrient-like proxies such as $\delta^{13}C$ because the source/sink term for ^{14}C (radiodecay) is known accurately. By radiocarbon dating pairs of BF and PF from the same sample, apparent ventilation ages can be calculated [*Broecker et al.*, 1990; *Adkins and Boyle*, 1997; *Meissner et al.*, 2003], but uncertainties remain. *Adkins and Boyle* [1997] showed that ventilation ages should account for changes in atmospheric ^{14}C activity, but this will not be practical until the ^{14}C calibration is better known for the LGM and early deglaciation (*Hughen et al.* [2004] have made progress on this topic). They also pointed out that the measured BF age is influenced by the age of the surface water parcel when it sinks, and at high southern latitudes this is unknown for the LGM. Finally, it should be noted that ventilation ages refer only to the ^{14}C age of a water mass and cannot be interpreted by themselves in terms of mass transport [*Wunsch*, 2003].

[22] In principle, to measure ventilation ages only requires sufficient PF that lived in near-surface waters exchanging with the atmosphere, and sufficient BF. Unlike $\delta^{13}C$, there appear to be no significant "vital effects" on $\Delta^{14}C$, but care must be taken in avoiding problems of changing abundances and sedimentation rates [*Hutson*, 1980; *Broecker et al.*, 1999]. This is best accomplished by studying cores with high accumulation rates and by documenting abundance changes in the foraminifera. In the present study the abundance of BF is well documented (Figures 2a–2j and 3), but because of the large number of samples involved, PF could not be counted. Instead, where possible, measurements were made on *G. ruber* because it is the only surface dwelling PF that is consistently abundant in glacial as well as interglacial sediments. This is an unconstrained source of error, but the consistency in the measured ventilation ages and the general agreement with $\delta^{13}C$ and Cd/Ca suggests that it is not fatal.

4.2.1. LGM Reconstruction

[23] Apparent ventilation ages for the LGM are only available for water depths >2.5 km in the BBOR region (Figure 8a and Table 2). Pairs of data from three new cores confirm the *Keigwin and Schlegel* [2002] result that >3 km the ventilation age of the deep western North Atlantic was at least 1000 years, a value first predicted by a zonally averaged ocean circulation model [*Stocker and Wright*, 1998]. In fact, the greatest apparent ventilation age is about 1500 years for samples >4 km, close to the 1600 year ventilation age of the deep North Pacific today [*Broecker et al.*, 1990]. This is consistent with the very low $\delta^{13}C$ (~ -0.5‰) in the glacial deep western North Atlantic, which is the same as the deep North Pacific above 4 km [*Keigwin*, 1998]. The lack of contrast in $\delta^{13}C$ between these basins might suggest that they were filled with the same water mass, of probable southern origin, although other studies have detected small differences that might still require some basin-basin fractionation of nutrients above ~3500 m [*Boyle and Keigwin*, 1985]. Whereas *Ninnemann and Charles* [2002] make a convincing case that the very

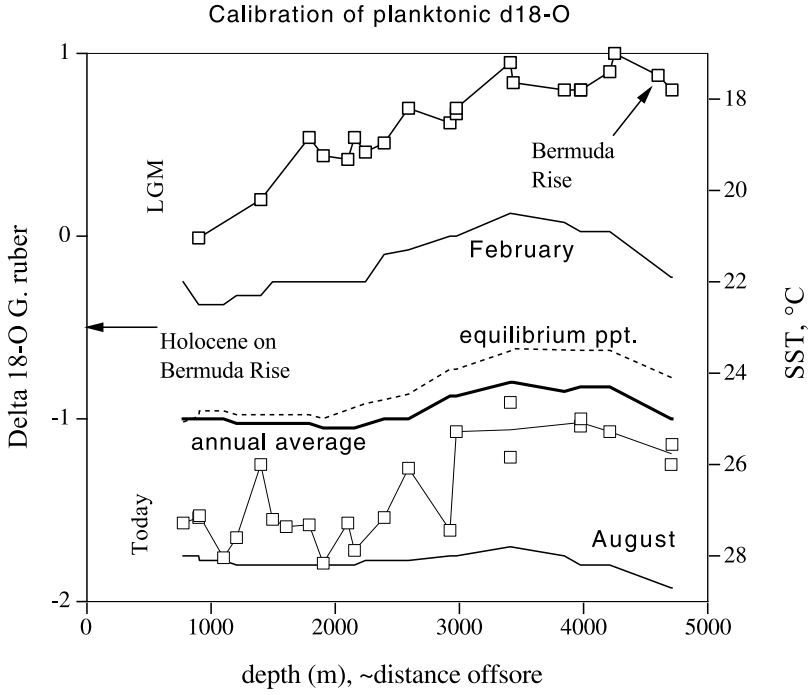

Figure 6. Trends in surface ocean properties from $\delta^{18}O$ of planktonic foraminifera from core tops and from the LGM time slice, as a function of water depth. For core tops and for the LGM, the planktonic foram data are shown as open squares. The core top data are compared to climatological SSTs at the same location [*Robinson et al.*, 1979] for the annual average, for August, and for February. Using the same method and assumptions for the late Holocene study of the Bermuda Rise [*Keigwin*, 1996] (Figure 1), the $\delta^{18}O$ of calcite precipitated in equilibrium with annual average SST is shown as a dotted line.

low $\delta^{13}C$ in *Cibicidoides* ($\sim -0.8‰$) from high southern latitudes is not an artifact of some process such as carbon rain rate [*Mackensen et al.*, 1993], there is still a problem. The fact that the deep North Atlantic is relatively enriched in ^{13}C requires either a separate northern source of bottom water, or mixing with other nutrient depleted water. In the deep North Atlantic, the very large apparent ventilation ages seem to rule out a significant northern source.

[24] At the shallow end of the LGM reconstruction, the best LGM ventilation probably occurred above ~2200 m, the depth of the front indicated by the benthic $\delta^{13}C$ data here (Figure 7d) and elsewhere [*Oppo and Lehman*, 1993; Curry and Oppo, submitted manuscript, 2004]. Although the LGM is confidently identified at shallow BBOR sites by PF $\delta^{18}O$, the scatter in BF $\delta^{18}O$ (Figures 2a–2d) shows that downslope transport might compromise BF ^{14}C dates on those samples. Thus, although the shallowest apparent ventilation age (~2.5 km) for the LGM is also the lowest, at present there are no data from above 2.3 km where the $\delta^{13}C$ is greatest.

4.2.2. Younger Dryas Reconstruction

[25] For the YD, ventilation ages are now available for many levels in the entire water column, from ~4.6 km on the Bermuda Rise to 1.8 km on the Carolina Slope (Figure 8a, Table 2). The benthic front that is defined by $\delta^{13}C$ is clearly evident in the abrupt change in ventilation ages between about 2.4 km and 2.2 km (Figure 8a). In the deep waters, YD and LGM ventilation ages are the same, and as with the LGM, the YD has a maximum apparent ventilation age as much as 1500 years >4 km. Using the newer and more precise dates from the YD on the Bermuda Rise increases the YD ventilation age there closer to the deep water average of about 1000 years (Figure 8a). For GNAIW, ages are all <500 years, which means this water mass was probably at least as well ventilated as it is today (as discussed above, benthic $\delta^{13}C$ suggests better ventilation). This supports previous interpretations based on benthic $\delta^{13}C$ and Cd/Ca measurements from Bahamas cores [*Slowey and Curry*, 1995; *Marchitto et al.*, 1998].

[26] Because the average age of PF at the YD time slice identified here is 11.25 ± 0.25 ^{14}C kyr BP, the ~1000 year contrast in ventilation ages across the front at ~2.3 km must be driven largely by the BF ^{14}C data which average close to 12 kyr ^{14}C cal years BP for cores >2.3 km (Figure 8b). Although Figure 8a shows relatively small 1σerror bars on the difference between the ^{14}C analyses, one core actually had YD BF younger than PF. This is probably an impossible situation in the present oceanographic setting, and highlights the fact that other errors due to bioturbation and abundance changes are no doubt hidden in the data. The influence of bioturbation can work the other way as well. As described above, the PF age on the YD BF peak in core 26GGC is probably too young, but the conventional ^{14}C age of 12.0 kyr ^{14}C cal years BP is probably reliable because it is in line with other BF measurements from cores >2.3 km. Thus, in summary, although the measurements are precise,

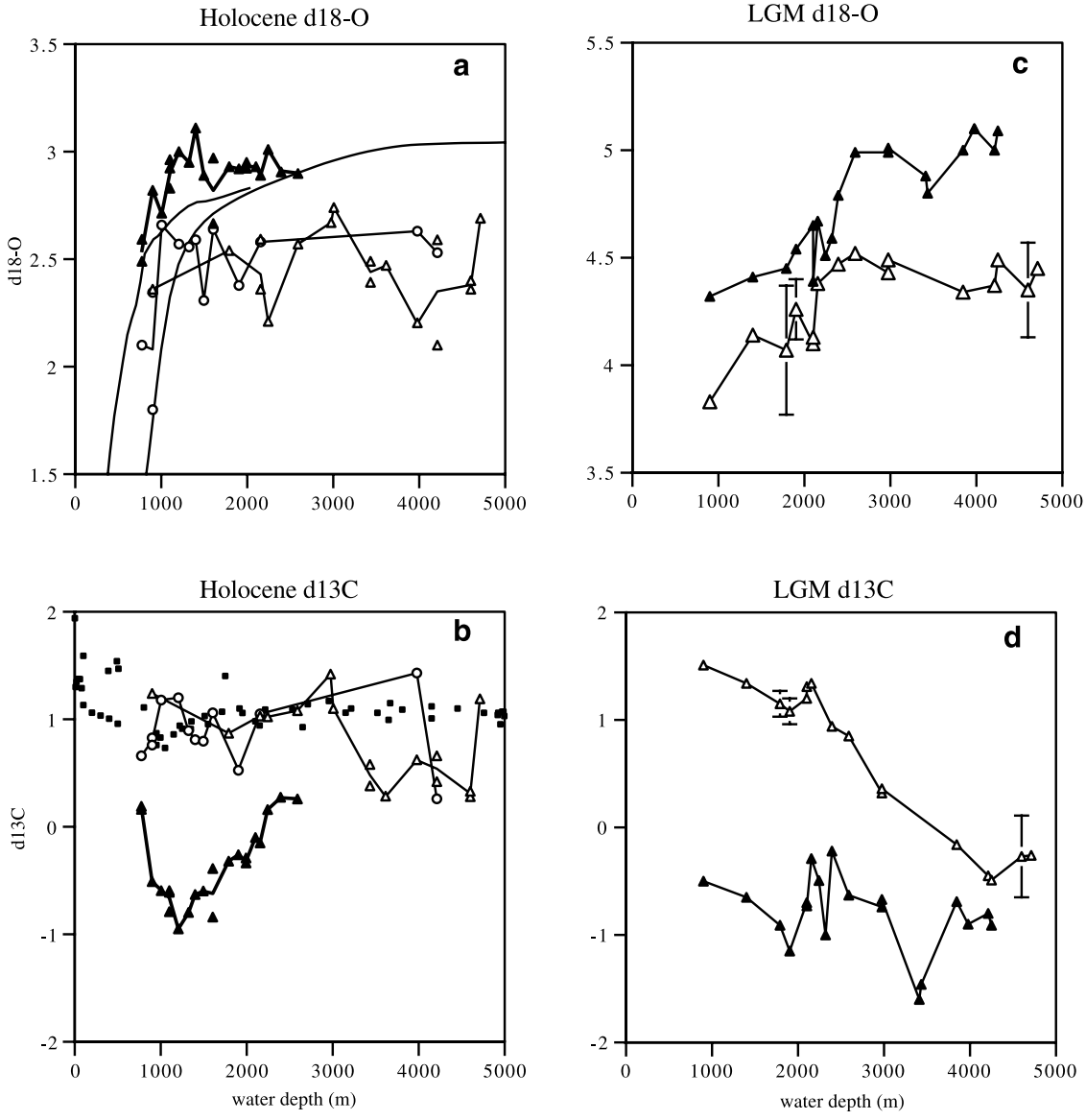

Figure 7. Summary of benthic foram stable isotope data from (a and b) core tops and (c and d) the LGM time slice. *U. peregrina* data are solid triangles, *C. wuellerstorfi* data are open triangles, *Cibicidoides* spp. data are open circles, and $\delta^{13}C$ of ΣCO_2 data are solid squares. Neither Holocene *Cibicidoides* nor *U. peregrina* results are very consistent with either the trend in expected oxygen isotope equilibrium precipitation of calcite (thin lines for a deep and a shallow site) (Figure 7a), or the $\delta^{13}C$ of ΣCO_2 in the water column (solid squares from GEOSECS and this study) (Figure 7b). Although none of the core tops are likely to be zero age, and there may be undetected and meaningful $\delta^{13}C$ trends in the Holocene, it is notable that $\delta^{18}O$ of the core top *U. peregrina*are less variable than the *Cibicidoides* data where they co-occur. However, the *Cibicidoides* data from the LGM (Figures 7c and 7d) display much more consistency among themselves and with results from previous studies.

the ventilation ages are probably accurate to only within a few hundred years.

[27] From this analysis three conclusions can be drawn. First, the relatively high apparent ventilation ages in the western North Atlantic were about the same for both the YD and the LGM. This may imply that the extent of replacement of NADW by old, most probably southern source water, was about the same for these two time intervals. Similar ventilation for these two intervals is also in accord with Pa/Th results from the Bermuda Rise [*McManus et al.*, 2004]. However, it differs from the interpretation based on nutrient-like proxies, where deep sites show greater nutrient enrichment during the LGM than the YD. Second, there was a strong contrast in ventilation during the YD at ~2.3 km between GNAIW and glacial deep water. Third, based on $\delta^{13}C$ of *C.*

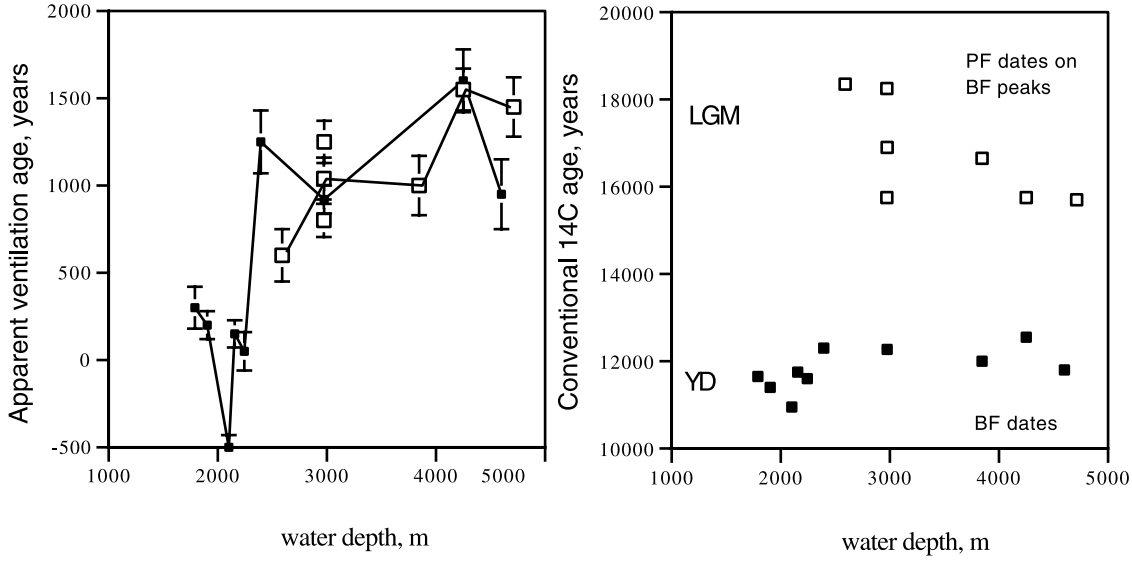

Figure 8. Summary of apparent ventilation ages for (a) the YD and LGM time slices, and (b) benthic foram dates during the YD and planktonic dates on the LGM benthic peaks. In Figure 8a the 650 year apparent ventilation age for the YD is omitted because of the large error on the original PF date [*Keigwin and Jones*, 1989]. For each panel, YD data are solid squares, and LGM data are open squares.

wuellerstorfi, the deep North Atlantic and deep North Pacific may have been filled with the same water mass during the LGM in the depth range 3.5 to 4.0 km.

4.2.3. Radiocarbon Ventilation Ages and Modeling

[28] Despite the limitation of measuring ventilation ages only at peaks of foraminiferal abundance, they have a strong advantage over nutrient based proxies in ocean modeling. This is because, to a first approximation, a full nutrient and carbon cycle need not be modeled to simulate ^{14}C in the ocean [e.g., *Fiadiero*, 1982; *Marchal et al.*, 1999]. Recent studies have made good progress integrating ^{14}C-based ventilation ages into coupled ocean-atmosphere general circulation models to better understand changes in ocean ventilation and transport.

[29] Using a coupled ocean-atmosphere-sea ice model, *Meissner et al.* [2003] found that 40% weakening of NADW is most consistent with the available ^{14}C-based ventilation ages in the Atlantic Ocean [*Broecker et al.*, 1990; *Keigwin and Schlegel*, 2002]. Their model produced a strong front at ~2 km, between young intermediate water and underlying older deep water, and predicted top to bottom age differences of as much as 1500 years throughout much of the North Atlantic west of the mid-Atlantic Ridge. This result is in striking agreement with the more extensive ^{14}C data set presented here. In another study using the same model, *Schmittner* [2003] simulated expanded LGM sea ice in the Southern Ocean and found that reduced atmospheric gas exchange can increase ^{14}C ages by 100 years at the same time that the flux of saltier AABW increases. As noted earlier by *Campin et al.* [1999], this shows how radiocarbon age can become greater than actual age in the Southern Ocean. The net effect of the reduced gas exchange and the increased transport increases the top-to-bottom age differences in the deep western North Atlantic by ~300 years [*Campin et al.*, 1999; *Schmittner*, 2003]. This is similar in extent to the ventilation decrease originally measured by *Broecker et al.* [1990], but the newer data from the BBOR region require that flux of NADW was dramatically reduced or eliminated entirely.

[30] In summary, radiocarbon ventilation ages suggest that, during both the YD and the LGM, young GNAIW replaced young NADW as the northern source water in the Atlantic. On the basis of trace metal ratios and $\delta^{13}C$, it was probably more nutrient-depleted than upper NADW today. Much older, and nutrient rich, southern source bottom water filled the western North Atlantic basin below GNAIW, and accounts for the increased apparent ventilation ages measured in the BBOR region. This would be a step toward satisfying *Wunsch*'s [2003] contention that increased windiness should lead to increased transport during cold episodes, if the preformed age of southern source waters increased even more than the 300 years predicted by models, and/or if increased ageing occurred in deep recirculating gyres. This scenario would be consistent with the fact that deep sediment drifts in the North Atlantic were at least as active during the LGM as they are in the Holocene [*Keigwin and Jones*, 1989], but we are still left without an estimate of southern source transport to the western subtropical North Atlantic basin. Although we do not have a direct measure of GNAIW transport either, if *Lynch-Stieglitz et al.* [1999] are correct that northward flow through Florida Strait was cut by about two thirds during the LGM, then GNAIW flux must have been about two thirds that of NADW today because there was no deep northern source water at all. Although many of these conclusions have been reached independently in the past by others, the ^{14}C ventilation data are important because they complement

the nutrient-proxy data and because they provide powerful constraints in ocean circulation models which will get us closer to reliable estimates of paleotransport.

4.3. Unfinished Business

[31] The paired BF-PF ventilation age method, as used here and by *Keigwin and Schlegel* [2002], is completely dependent on the presence of BF abundance peaks, yet it is not known why, where, and when these peaks occur. *Keigwin and Schlegel* [2002] considered three possibilities: winnowing of clay and silt that could concentrate the sand fraction, control of benthic fauna by bottom water mass changes, and changes in productivity. They used mass accumulation rate arguments to reject the first possibility in cores from ~3 km. Although we have not calculated BF accumulation rates here, the new data show very large spikes in abundance over background values without evidence of major oscillations in sedimentation rate. For example, the deglacial section of 51GGC has a uniform sedimentation rate of ~20 cm/kyr (Figure 4) with *U. peregrina* abundance peaking at ~40/g (Figure 2a), yet the LGM, which probably was winnowed, has a very low rate of accumulation and only small benthic peaks. Control of the benthic population by water mass, though once a fashionable idea, seems unlikely because the YD peak in *U. peregrina* abundance extends from as shallow as 1800 m to as deep as 3800 m (Figures 2a–2j), yet the major boundary between water masses is inferred to be at about 2300 m. Furthermore, peaks in abundance of *U. peregrina* during the LGM give way to peaks of *N. umbonifera* below about 3800 m, yet available evidence does not support a shift in water mass at that depth.

[32] This leaves us with benthic faunal control by surface ocean fertility, an idea that is attractive because it is known to occur elsewhere in the ocean [*Zahn et al.*, 1986; *Loubere*, 1991, 2000; *Keigwin et al.*, 1992]. Because most of the cores discussed here come from the geographically restricted BBOR and Carolina Slope region, greater export production of organic carbon should affect sites at all water depths. For the YD, this appears to be true because all the BF peaks have the same PF age (~12,900 cal years BP). This is only ~100 years older than the maximum in atmospheric $\Delta^{14}C$ identified in Cariaco Basin sediments in the earliest YD [*Hughen et al.*, 1998]. *Hughen et al.* [1998] argued that the higher ^{14}C activity of the atmosphere at that time was caused by a shutdown of NADW formation, an association that is fully supported by the ventilation age data (within ~100 years). However, they also suggested that the gradual fall in $\Delta^{14}C$ following the initial maximum was caused by the subsequent initiation of GNAIW flow. This has been questioned by *Muscheler et al.* [2000] and *Marchal et al.* [2001], whose model results show the decreasing trend in $\Delta^{14}C$ can be accounted for by ^{14}C production changes alone. The ^{14}C data presented here support those model results because the maximum apparent ventilation <2.3 km was already established early in the YD. Thus it is reasonable that there is a link between the strongest YD cooling at the beginning of that episode, as shown by minimum ice core $\delta^{18}O$ [*Dansgaard et al.*, 1993; *Grootes et al.*, 1993], the sharp spike in atmospheric $\Delta^{14}C$, the pronounced contrast between intermediate and deep ventilation ages, and surface ocean fertility in the western Sargasso Sea. Increased windiness may have led to deeper winter mixed layer, surface nutrient recharge, and higher fertility. If the surface ocean reservoir effect increased above the 400 years assumed here, that may also account for the 100 year age difference between the age of our YD time slice and the Cariaco Basin data.

[33] This scenario applies to the YD where we are dealing with a relatively narrow time slice, but it does not work as well for the LGM. Although *Keigwin and Schlegel* [2002] dated three BF abundance maxima of LGM age from cores near 3 km (18.2, 19.6, 21.1 cal years BP), none of the other cores have more than a single dated BF event. The LGM date from the new core at 2.6 km (43GGC; Figure 2g) is equal to the oldest LGM event in the cores from 3 km (Figure 8b), but this core has neither of the younger events. At the deep water extreme, 22JPC (Figure 2j) has the youngest BF peak identified previously at 3 km, but none of the older events. It could be argued that the older events lie deeper in the cores (or beyond the 5 m reach of our gravity cores), but this does not account for the absence of the younger events. Perhaps the simplest explanation is that there are small gaps in the stratigraphic record, but this will be difficult to prove.

5. Conclusions

[34] Stratigraphies and chronologies have been developed for the past ~20 kyr using numerous piston and gravity cores from water depths between about 1 and 5 km along the continental margin and sediment drift locations in the western subtropical North Atlantic. Stable isotopes and benthic foraminiferal abundances were used to identify the best cores for monitoring ocean ventilation changes using AMS ^{14}C dates. Although the focus of this work is the radiocarbon-based ventilation estimates, the stable isotope data also contribute to understanding climate change in this region. Major conclusions are:

[35] 1. $\delta^{18}O$ of *G. ruber* in core tops generally follows the trends expected for equilibrium precipitation of calcite if the dominant isotope effect is the offshore decrease of SST in the study region. During the LGM the SST was at least 4°C colder than today, in the absence of local salinity change, and surface water $\delta^{18}O$ was about the same from the Bermuda Rise to the Blake-Bahama Outer Ridges region.

[36] 2. Core top $\delta^{18}O$ data on *U. peregrina* are less noisy than *Cibicidoides* in this region. Core top *U. peregrina* shows that $\delta^{13}C$ of this species is unreliable as a tracer for $\delta^{13}C$ of ΣCO_2 because it is strongly affected by carbon rain rate. Although this was not designed as a core top calibration study and the core tops here may not be modern, results on *C. wuellerstorfi* are especially variable below ~3 km, as reported previously on the Bermuda Rise. Nevertheless, glacial age results are consistent with those from other locations: $\delta^{13}C$ of *C. wuellerstorfi* indicates substantial nutrient depletion above ~2 km, and deep nutrient levels the same as in the deep North Pacific.

[37] 3. For both the YD and LGM time slices, the deep western North Atlantic had the same ^{14}C ventilation ages. This suggests the ocean's mode of operation for YD and LGM was the same, but it differs from interpretations based on nutrient proxies such as $\delta^{13}C$. These show a continuous

decrease with increasing water depth, at least below ~2 km. For the YD, a strong front was present at about 2300 m, separating waters below with apparent ventilation ages of ~1000 years from upper waters with apparent ventilation ages of <500 years. Because the YD time slice is a brief event and PF ^{14}C ages are on average 12.9 cal years BP, it is evident that BF-PF was driven by the change in BF $\Delta^{14}C$.

[38] 4. Although reduced gas exchange caused by expanded sea ice in the southern ocean can artificially increase the ^{14}C age of deep North Atlantic waters, the ventilation ages measured here require substantially reduced production, or (more likely) elimination of NADW during severe climate. If NADW was completely eliminated, and Gulf Stream transports estimated by *Lynch-Stieglitz et al.* [1999] are correct, then GNAIW export must have been about two thirds of today's NADW transport.

[39] 5. Benthic foraminiferal abundance peaks were probably caused by stronger winter mixing and a more productive surface ocean, at least for the YD. At 12.9 cal years BP, the age of the YD event in the western subtropical North Atlantic is virtually identical to the age the peak in atmospheric $\Delta^{14}C$ from the Cariaco Basin record. This suggests coincidence of the coldest part of the YD, strong winter deep mixing and fertility of the surface ocean, strong reduction in NADW, strong production and nutrient depletion of GNAIW, and strong production of southern source water.

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